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2016 J. Phys.: Conf. Ser. 718 022009

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Overview and Status of Advanced Interferometers for Gravitational Wave Detection

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Abstract. The world-wide network of km-scale laser interferometers is aiming at the detection of gravitational waves of astrophysical origin. The second generation of these instruments, called *advanced detectors* has been, or is in the process of being completed, and a first observational run with the Advanced LIGO interferometers has been performed late in 2015. The basic functionality of advanced detectors is discussed, along with specific features and status updates of the individual projects.

1. Introduction

Gravitational waves have been predicted as a consequence of the general theory of relativity 100 years ago. Besides directly confirming this exciting phenomenon, gravitational wave detectors are expected to become a new tool for astronomy, astrophysics and cosmology, and to facilitate a direct test of general relativity with respect to gravitational waves and their source object properties.

Non-axisymmetric acceleration of masses causes a dynamic strain of space-time, traveling as a wave at the speed of light. First attempts to measure gravitational waves were started in the 1960's with resonant mass detectors [1]. Some time after the advent of the laser, interferometry was proposed as an alternative means of measurement, potentially reaching higher sensitivity over a wider frequency band. Several prototype interferometers around the world explored and refined this technique [2, 3, 4, 5, 6], informing the design of detectors with longer interferometric arms. The initial network of these larger laser interferometers, consisting of two LIGO detectors [7] in the US, Virgo [8] in Italy, GEO 600 [9] in Germany, and TAMA 300 [10] in Japan, reached a milestone of sensitivity around 2005. A number of data-taking runs with varying detector participation took place until 2011, with no gravitational wave detections made, consistent with expected astrophysical event rates [11]. A second generation of instruments, the *advanced detectors* employ several improvements (as detailed below) aiming for a roughly 10-fold increase in sensitivity. These are *Advanced LIGO* [12], *Advanced Virgo* [13], and KAGRA [14]. The GEO 600 detector employs an incremental upgrade program testing a number of advanced techniques [15].

Figure 1 shows achieved strain noise curves for the detectors of the initial network, together with design curves for advanced detectors. With a 10-fold increase in sensitivity of the advanced



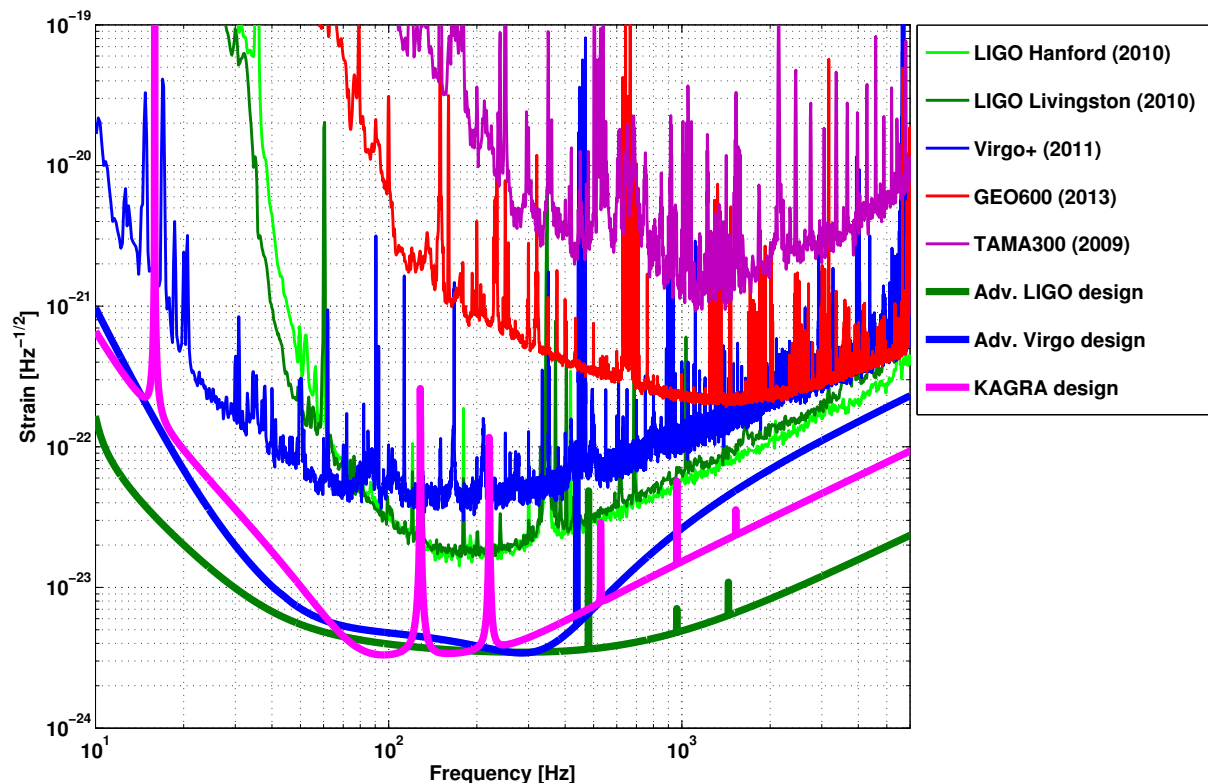


Figure 1. Strain noise curves as experimentally realized for the initial detector network and planned (design) for the advanced detectors. The traces represent detector output due to instrument inherent noise, calibrated to equivalent strain of space and displayed as amplitude spectral density.

detectors, the sampled volume of the universe increases by a factor 1000, making frequent gravitational-wave detections, in particular from binary coalescent sources, very likely [11].

2. Advanced interferometer overview

Fig. 2 shows a simplified optical layout of advanced interferometers. The core instrument facilitating gravitational wave measurement comprises four optical resonators arranged around a Michelson interferometer, a configuration called *dual recycled Fabry-Perot Michelson*. The building blocks, according to Figure 2, of the dual recycled Fabry-Perot Michelson can be broken down as this: Mirrors ITMX and ETMX, as well as ITMY and ETMY form two Fabry-Perot cavities within the long arms (also called *arm cavities*) of a Michelson interferometer (MI) using BS as the beam-splitter. The laser light is resonant in these two arm cavities, with almost all of the light being reflected by the arms. The Michelson interferometer, consisting of the beam-splitter and the resonant arm cavities, is set to an operating point at which almost all of the light recombined at the beam-splitter is reflected towards the input port from where the laser light enters the optical system. This is called the *dark fringe* condition, since almost no light leaves the interferometer towards the output port. At the dark fringe operating point, another Fabry-Perot cavity is formed by the mirror PRM and the Michelson interferometer, a technique called *power recycling*. Power recycling serves to increase the circulating power in the interferometer, including the arm cavities. Mirror SRM (which is an addition in Advanced Detectors), forms a Fabry-Perot cavity (the signal recycling cavity) with the Michelson, which is used to shape the

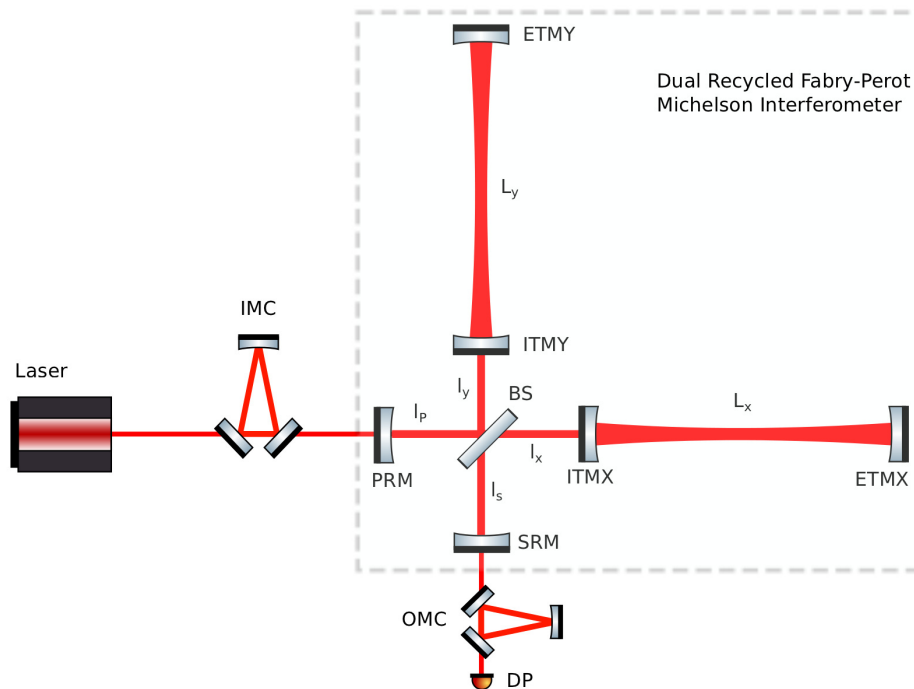


Figure 2. Simplified optical layout (not to scale) of an advanced interferometer for gravitational wave detection. A solid state laser and input filter (mode cleaner IMC) provide light to the main interferometer, a dual recycled Michelson interferometer with Fabry-Perot cavities in the arms. An output filter (mode cleaner OMC) is implemented before detection of the output light on photodetector DP.

optical frequency response, a technique that generally can be called *signal recycling* [16]. The combination of power recycling and signal recycling is often called *dual recycling* [16]. In the case of Advanced detectors (LIGO, Virgo, KAGRA), signal recycling is operated in the *resonant sideband extraction* (RSE) [17] regime. This means that gravitational wave sidebands generated in the long arms effectively experience a shorter storage time in the arm cavities than the carrier light does, and thus are effectively *extracted* from the arms.

The mirrors ITMX, ITMY, ETMX, and ETMY can also be called test-masses, denoting their role of serving as quasi free-falling objects, with the laser light testing for gravitational-wave induced strain in the space between them. The test masses have to be isolated from ground vibration (which may be indistinguishable from gravitational-wave induced strain of space) by sophisticated seismic isolation systems, including multi-stage pendula. All optics and suspensions are housed in ultra-high vacuum (UHV) enclosures, which are among the largest UHV systems on the planet. Sophisticated control systems are required to keep all suspended optics in place to precisions better than 1 pm.

The major improvements implemented in advanced detectors compared to the initial network detectors are:

- Improved seismic isolation (LIGO), or underground operation (KAGRA).
- Lower thermal noise due to monolithic suspension [18] of the test masses and larger beam sizes (LIGO, Virgo), or cryogenic operation (KAGRA).
- Reduced quantum (shot) noise due to higher circulating power, facilitated by higher recycling gains and higher input laser power.

- Sophisticated thermal compensation systems, to reduce the effects of thermal aberrations due to high power operation.
- Improved stray light control with extended use of baffles and in-vacuum beam detection.

Table 1 shows some parameters for the current four gravitational wave detector designs in comparison. The GEO detector does not feature Fabry-Perot cavities in the long arms, but has once folded arms instead.

Table 1. Some design properties of each of the four gravitational wave detectors.

	Adv. LIGO	Adv. Virgo	KAGRA	GEO-HF
arm length	4 km	3 km	3 km	2×600 m
power recycling gain	44	39	11	900
arm power	800 kW	700 kW	400 kW	20 kW
# pre-isolation stages	3	1 invert. pend.	1 invert. pend.	1
# of pendulum stages	4	7	5	3
mirror mass	40 kg	42 kg	23 kg	6 kg
mirror material	fused silica	fused silica	sapphire	fused silica
temperature	room	room	cryogenic, 20 K	room

3. Status of interferometer projects

In this section aspects unique to a particular design are highlighted and an update of the individual interferometer projects is given.

3.1. Advanced LIGO

The Advanced LIGO project, approved in 2008, commenced with hardware installation in 2010. The project finished with the formal acceptance at the end of March 2015, moving the detectors to the commissioning and operation stages. The most important change from initial LIGO to Advanced LIGO is the implementation of improved seismic isolation of the test masses, consisting of 7 stages: A first stage with inertial sensors and hydraulic actuators outside the vacuum chambers is used to counteract large-amplitude low-frequency motion of the ground. Then two stages with a combination of active and passive isolation are located within the vacuum system, and finally a test-mass suspension consisting of four pendulum stages provides passive isolation above the pendulum resonances of about 0.5-2 Hz. Besides the increased beam size and monolithic test-mass suspension mentioned above, another change from initial LIGO is the implementation of so-called stable recycling cavities, which allow for an easier control of the interferometer, in particular for high power operation. The stable recycling cavities are realized by adding two more mirrors to the paths labeled l_P and l_S in Figure 2. The laser light source for Advanced LIGO is a Nd:Yag solid state laser with two amplifier stages, providing up to 200 W of light continuously [19]. As a means to compensate thermal aberrations in the optics from high power operation, a system of ring-heaters to change the radius of curvature of the test-masses is employed, as well as a system of CO₂ lasers for heating compensation optics suspended within the recycling cavities.

After the installations were completed, a first *lock* (the transition to a linear and sensitive operating regime) was achieved at the Livingston detector in April 2014 with the help of auxiliary laser systems to lock the long arm cavities [20]. A rapid progress in strain sensitivity followed over the next months, such that later in 2014 a sensitivity range for a neutron star binary coalescence source of about 60 Mpc was reached (for an average source orientation and a signal-to-noise ratio of 8). Figure 3 shows the performance of the LIGO Livingston detector as of

October 2015, as well as the late initial LIGO strain noises and the Advanced LIGO design noise. The performance of the LIGO Hanford detector is very similar to the Livingston one. The two LIGO detectors were transitioned to an observational mode in August 2015 and entered

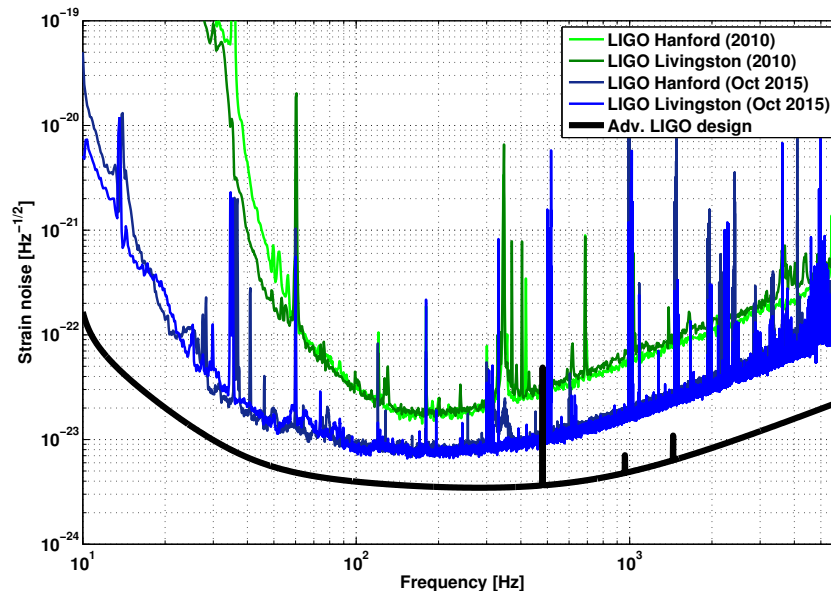


Figure 3. Measured strain noise curves for late initial LIGO detectors (2010), for the early (current) stage of Advanced LIGO (Oct. 2015), and planned strain noise for Advanced LIGO. The noise curve of Oct. 2015 represents a sensitivity range for binary neutron star coalescence of 71 ± 7 Mpc.

the first observational run (O1) of the Advanced detector era in September 2015 (foreseen to last until January 2016). As of December 2015, the dual coincidence observing time in O1 is about 45 % with binary neutron star inspiral ranges of 65-80 Mpc.

3.2. Advanced Virgo

The Advanced Virgo project was funded in 2009 and besides France and Italy (the stakeholders of the initial Virgo detector), contributing countries are the Netherlands, Poland, and Hungary. The seismic isolation system of Advanced Virgo is very similar to the one employed in initial Virgo: The test masses are suspended from so-called *superattenuators*, with an approx. 8 m long chain consisting of 7 pendulum stages, suspended from one inverted pendulum erected from the ground [21]. A conceptual drawing of a super-attenuator is shown on the left hand side of Figure 4.

Due to the super-attenuators, Virgo had the best sensitivity in the initial detector network below 80 Hz, as can be seen in Figure 1. Modifications of the suspensions for Advanced Virgo were required in particular for the last stage, carrying heavier test masses (42 kg), as well as compensation plates and baffles for stray-light prevention. Four large cryotrap (liquid-nitrogen cooled surfaces) have been added to the ends of the long arms in order to reduce residual gas pressure in the arms. A number of dedicated auxiliary vacuum chambers have been added to house seismically isolated optics tables (an example can be seen on the right hand side of Figure 4). These tables facilitate sensing of auxiliary light beams under seismically isolated conditions with the purpose of preventing light of auxiliary beams to back-scatter into the main interferometer. Other novelties of Advanced Virgo include in-vacuum conversion of analog to

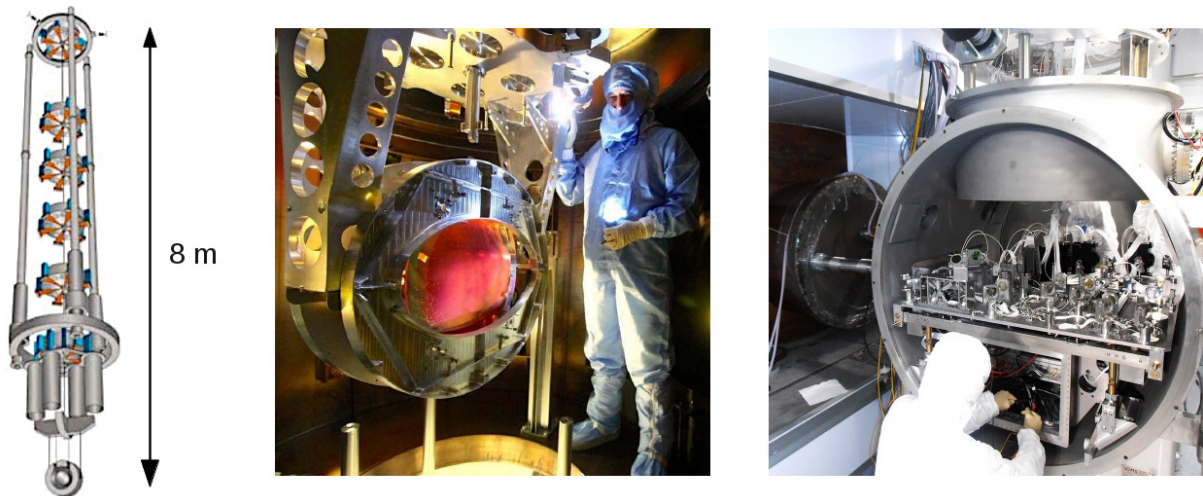


Figure 4. Conceptual drawing of a superattenuator (left), an image of the suspended beam-splitter (middle) and a view of a suspended bench in an auxiliary tower (right). Images courtesy of EGO/Virgo.

digital signals, and digital handling of radio-frequency signals. Both of these techniques reduces the required amount of in-vacuum cabling, and also can increase flexibility for obtaining control signals.

As of October 2015, the input mode cleaner system is operational and characterized. The beam-splitter as well as the test masses ITMY and ITMY are successfully installed and suspended from the super-attenuators. Figure 4 (middle) shows an image of the suspended beam-splitter. The completion of installation is expected for early in 2016, followed by a period of commissioning. The goal is to join the LIGO detectors in their second observational run in 2016.

3.3. KAGRA

The Japanese KAGRA detector (formerly known as LCGT) is not an upgrade to an existing project, but a new interferometer in an entirely new facility at the Kamioka mine in Hida city, Gifu Prefecture. Two outstanding features distinguish KAGRA from Advanced LIGO and Advanced Virgo, which are the underground location of the facility and the cryogenic operation of the test masses at 20 Kelvin. The design of KAGRA has been informed by experience from TAMA 300 and the underground cryogenic CLIO interferometer [22]. Underground operation promises significantly reduced seismic noise, about a factor of 100 less than at the TAMA 300 site in Tokyo, for frequencies above 1 Hz. Cryogenic operation is one means to lower thermal noise of the test-mass suspension, as well as of the mirror's highly-reflective coating. KAGRA will employ test masses made of Sapphire, which (at cryogenic temperatures) has a lower thermal conductivity than fused silica and thus reduces impact from thermal aberrations. The test-masses will mostly be cooled by conductive cooling via their suspension rods, which are made of sapphire as well. The suspension system of KAGRA consists of a 14 m long pendulum chain hanging from a dedicated cavern in the underground laboratory [23]. A particular challenge of the project is the integration of the cryogenic system with the suspension chain without degrading the seismic isolation performance.

The excavation of the two 3 km long tunnels and caverns for the vacuum systems of KAGRA started in 2012 (delayed due to the earthquake in 2011), and has been completed in March

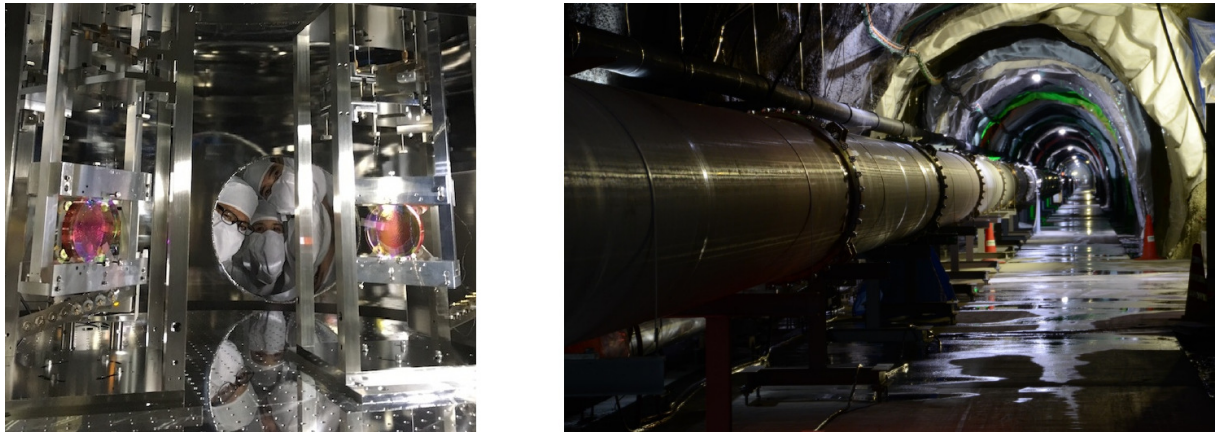


Figure 5. Left: KAGRA suspended input mode cleaner optics; right: x-arm beam tube and tunnel. Images courtesy of KAGRA and S. Miyoki.

2014. As of November 2015, vacuum beam tubes in both arms have been installed and leak tested. The four main cryostat chambers have been installed, as well as a clean booth for the laser. All mirrors for the input mode cleaner are suspended. See Figure 5 for a view of the mode cleaner mirrors and the x-arm tunnel of KAGRA. After an initial test-interferometer setup called *iKAGRA*, installation of the baseline cryogenic KAGRA detector *bKAGRA* will start in 2016. First observational runs with *bKAGRA* are foreseen for 2017/2018, then joining the international network of gravitational wave detectors.

3.4. GEO 600

GEO 600, the smallest of the operating detectors, may not be called an *advanced detector* in the sense the term is used to describe LIGO, Virgo, and KAGRA, in their prospect to routinely detect gravitational waves. Due to the shorter arm-length of the GEO detector, it could only see gravitational waves on rare particularly loud events. However, GEO 600 employs a number of so-called *advanced techniques*, which have been developed within the GEO collaboration, and have been validated in the GEO 600 detector, before being employed on the larger interferometers [24]. These techniques comprise the monolithic suspension of the test-masses, electro-static actuation of the test-mass, signal recycling, and ring heater thermal compensation, all of which have been employed since 2002. Instead of embarking on a complete re-build of a detector in the existing infrastructure (as LIGO and Virgo did for their advanced projects), GEO 600 was incrementally upgraded in a program called *GEO-HF*, aiming mostly for an improvement of sensitivity around and above 1 kHz [25, 15]. Due to the incremental nature of the upgrades, GEO 600 could collect data for more than 2/3 of the time since LIGO and Virgo began upgrading to their advanced programs. At the time of writing, the GEO 600 detector is collecting data during the first observational run of the Advanced LIGO detectors as well, however with a much lower chance than LIGO to detect gravitational waves.

A highlight technique of the GEO-HF program is the long-term application of squeezed vacuum, to lower quantum (shot) noise in the interferometer readout [26]. Squeezed vacuum application is now also planned as an early upgrade to Advanced LIGO and Advanced Virgo, and is expected to be used in all future gravitational wave observatories.

4. Conclusion

The world-wide network of advanced gravitational-wave detectors LIGO, Virgo, KAGRA, and the smaller GEO 600 detector, is now reality with the first observational run of this advanced

detector era having begun. The Virgo and KAGRA detectors are expected to join observational runs in 2016, and 2017/18, respectively. Opening a new window on the universe, gravitational wave astronomy is about to commence!

Acknowledgments

On behalf of the LIGO scientific collaboration the author acknowledges the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory, and the Science and Technology Facilities Council of the United Kingdom, the Max-Planck-Society, and the State of Niedersachsen/Germany for support of the construction and operation of the GEO 600 detector. The author thanks the Virgo collaboration and the KAGRA collaboration for material provided. This document has been assigned LIGO document number LIGO-P1500236

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